Paper ID: 15

Airfoil Passive Noise Reduction: A Comprehensive Analysis of Recent Advancements

Chaitanya Roy Chowdhury[1], Ehasanul Islam Rafi[2], Anik Molla[3], Hriday Kumar Gharamy[1], Md. Rokunuzzaman[1]
[1]Dept. of Mechanical Engineering,
[3]Dept. of Glass and Ceramic Engineering
Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh
[2]Dept. of Industrial and Production Engineering,
Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh
Email: 0chaitroy@gmail.com

Abstract

This paper provides a comprehensive analysis of noise reduction techniques in airfoils, with a focus on balancing noise reduction and aerodynamic performance. The need to reduce acoustic pollution and improve quality of life drives the motivation for noise reduction in airfoils. The implementation of various methods targets specific types of noise, including leading-edge noise, broadband noise, and tonal noise. However, these noise reduction measures often come at the expense of aerodynamic performance, necessitating a fine balance between noise reduction and efficiency. Recent advancements in the field include adaptive surface technologies and innovative materials that minimize noise without sacrificing aerodynamic smoothness. To assess the effectiveness of noise reduction techniques, the paper employs comparative analysis based on existing scholarly articles. This paper looks at a variety of design modification methods within the context of passive noise reduction techniques, such as leading and trailing edge treatments, porous materials, controlled diffusion airfoils, morphing wings, surface enhancements, and other advanced geometries developed by researchers. This study emphasizes the benefits of combining multiple techniques to achieve optimal results tailored to specific applications and design requirements. Tabular representations present the findings, clearly illustrating how these techniques influence noise mitigation and facilitating a more informed assessment of their practical impacts on airfoil design and performance.

Keywords: Airfoil, Aeroacoustics, Noise reduction, Aerodynamic efficiency

1. Introduction

The growing demand for aviation and drone technology in a variety of industries, including logistics and agriculture, has highlighted the critical issue of noise produced by airfoil systems. Because small wind turbines, drones, and other low-speed aerial vehicles operate at low Mach and Reynolds numbers, the noise produced by these systems, particularly during landing and takeoff, can be a significant nuisance and a potential health risk. This noise is primarily caused by aerodynamic interactions, particularly trailing edge noise (TE noise), which is defined as the scattering of vortical disturbances at the airfoil's trailing edge [1]. Such disturbances can cause both broadband and tonal noise, especially under specific flow conditions where laminar boundary layer instabilities create intense vortex shedding [2, 3].

Recent advances in aircraft design, particularly the introduction of high bypass ratio engines, have shifted the focus of noise reduction efforts away from jet engine noise and toward other sources, such as aerodynamic noise generated by airframe components [4]. The interaction between airflow and various airframe components, particularly airfoils, has emerged as a critical area of research. Understanding the mechanisms underlying flow-induced noise, such as pressure fluctuations and vortex dynamics, is critical to developing effective noise reduction strategies.

Efforts to reduce airfoil noise have yielded novel design solutions and material applications. Porosity, serration, and shape optimization techniques have all been shown to reduce trailing edge noise effectively. Additionally, adaptive flow control methods, such as boundary layer manipulation and cavity resonance exploitation, provide novel approaches to noise reduction. This review paper seeks to synthesize existing research on passive noise

control methods, thereby providing a comprehensive overview of the current state of knowledge in airfoil noise reduction. This paper aims to contribute to the ongoing discussion about improving the acoustic performance of airfoil systems in modern aviation by investigating the underlying noise-generating mechanisms and evaluating various mitigation strategies.

2. Passive Noise Control Mechanisms

2.1. Edge Treatment Methods

LE (Leading Edge) and TE (Trailing Edge) noise are two distinct types of self-generated noise that occur at different locations on the airfoil. They result from a variety of interactions, including pressure fluctuations in the wake and boundary layer (BL) or with the surface [5]. LE noise is produced at the front of the airfoil due to unique mechanisms, whereas TE noise is produced at the rear edge of the airfoil when the airflow from the upper and lower surfaces merges at the TE. The following sections go over specific passive methods for reducing both LE and TE noise.

2.1.1. Leading Edge Treatments

When turbulent air eddies strike the leading edge of an airfoil, they are quickly distorted, converting some of their energy into sound [6]. Amiet [7] conducted a significant study on this noise and developed a theory to predict how much sound an airfoil in turbulent airflow would make in the far field. The spanwise correlation length and the size of turbulent eddies in the airflow are the two most important factors in predicting this noise. Several researchers conducted experiments to investigate the process of leading-edge noise generation. Paterson and Amiet [8] measured the noise and unsteady surface pressure of a NACA-0012 airfoil placed behind a turbulence grid and concluded that noise prediction is possible if the incoming airflow characteristics are well understood. Kim et al. [9] investigated the aerodynamic and noise performance of a NACA 65-(12)10 airfoil by incorporating wavy, sinusoidal shapes into the leading edge (LE). They tested three different LE designs in a wind tunnel and discovered that these changes increased lift without increasing drag while also reducing noise across all frequencies. They also used PIV measurements to investigate how the wavy LE affected the airflow at the trailing edge (TE), discovering that the turbulence created at the undulation peaks aided in the reattachment of the flow after it separated. Lu et al. [10] investigated how to enhance the performance of bio-inspired wings featuring leading-edge (LE) tubercles. Their goal was to delay stalling and increase lift. To accomplish this, they generated a dataset of random wavy designs (Figure 1) using a parameterized method with F-spline curves and tested them with CFD simulations. The optimization was accomplished by combining a genetic algorithm with a Kriging Model-based response surface method. Vemuri et al. [11] discovered a reduction of up to 20 dB/Hz in near-field surface pressure PSD levels using leading-edge serration.

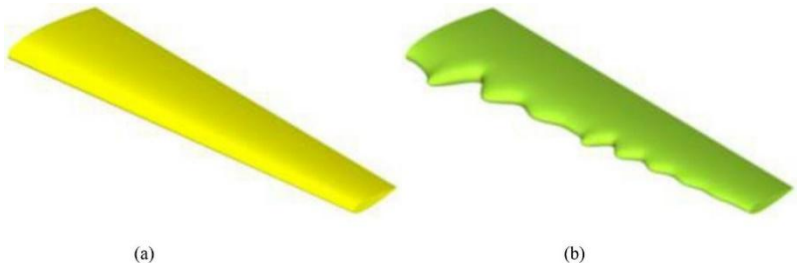


Fig.1. Comparison of the geometries for the two airfoils: (a) The smooth airfoil; (b) The wavy airfoil. [10]

2.1.2. Trailing Edge Treatments

Trailing-edge noise has sparked widespread interest in engineering applications such as wind turbines, marine propellers, rotorcraft, and automobile fans. While no definitive conclusion has been reached, several theories have been proposed to explain the trailing-edge noise mechanism [12]. It is proposed that quadrupole noise sources in the boundary layer and wake region become more effective due to a diffraction process at the sharp trailing edge, resulting in a cardioid directivity pattern [13]. Furthermore, sound at specific acoustic frequencies is thought to be amplified by an acoustic feedback mechanism near the trailing edge [14]. However, there is some disagreement about the exact nature of this mechanism and the origin of the feedback loop.

Trailing-edge protrusions are particularly effective at managing fluid flow over the upper surface of the wing, thereby reducing noise. It can cause the transition from laminar to turbulent flow, stabilizing the airflow along the suction side of the surface. This process delays vortex shedding, which is typically caused by laminar flow separation, thereby contributing to noise reduction [15]. Suryadi et al. [16] achieved a noise reduction of 7 to 10 dB with trailing edge modified with brush extention.

2.2. Porous Material

Previous research has thoroughly investigated the incorporation of porous materials into wing structures. Roger et al. [6] investigated turbulent flow caused by a grid designed to reduce noise at the leading edge of a NACA-0012 airfoil filled with steel wool. Even without material parameter optimization, the study demonstrated a 5 dB noise reduction. Geyer et al. [17] followed a similar approach, experimenting with various porous materials and grids that induce turbulence. He used microphone array techniques to measure acoustic performance and discovered that most porous profiles had significantly lower noise levels than non-porous profiles. Sarradj and Geyer [18], Geyer et al. [19], Tinetti [20], and Herr and Reichenberg [21] all looked into the potential of porous airfoils to reduce trailing-edge noise. These studies highlight the significant promise of porous materials in reducing flow-induced noise, while also emphasizing the need for a more nuanced understanding of how material properties, particularly static air flow resistivity, influence their effectiveness. In their comparative analysis of aero-acoustic wind tunnel data for porous and non-porous airfoils, Geyer and Sarradj [17] discovered that the properties of porous materials influence both overall sound pressure levels and spectral characteristics.

In general, porous materials near the trailing edge with low airflow resistivity allow more air to pass through. This helps to reduce the amount of broadband noise produced [22]. To reduce noise caused by turbulence interacting with the wing, Zamponi et al. [23] investigated the effect of porosity on surface turbulence. They subjected a solid and porous melamine foam airfoil to turbulence caused by an upstream rod. Using specialized techniques, they discovered that the ability of the porous airfoil to maintain its shape while reducing velocity variations had no significant effect on overall airflow. As a result, the turbulent energy of the stagnation area was reduced. Tests revealed that the porous material had a unique effect on low-frequency turbulence, resulting in lower noise levels. The researchers used the Rapid Distortion Theory [24] to explain the noise reduction. Rottmayer et al. used surrogate-based gradient-free optimization and an empirical noise model which achieved a noise reduction of about 8 to 10 dB [25].

2.3. Trailing Edge Serration

For airfoils, serrated trailing edges offer a promising way to reduce noise. Generally, flat plates inserted into the trailing edge have serrations applied to them to prevent bluntness-induced vortex shedding noise. These flat inserts, however, may reduce aerodynamic performance and lack the structural strength needed for wind turbines and propellers. Adverse pressure gradients at the inserts of highly cambered airfoils can lead to turbulent separation, which introduces additional noise sources. Consequently, extra noise may cancel out the noise reduction advantages of serrations, which would explain the inconsistent results [26]. According to Sumesh et al. [27], while increasing the height of the serrations increases the noise levels by approximately 16 dB, increasing the wavelength of the non-flat plate trailing edge serrations reduces the noise caused by narrowband vortex shedding. In addition, inclinations at the serration roots can reduce noise in the narrowband by as much as 20 dB, and a hybrid arrangement with a perforated plate greatly reduces noise in the broadband in the low and high frequencies. Yang et al. [28] achieved a maximum noise reduction of 4.43 dB in the 0–1000 Hz range with serrated trailing edge design of a pump-jet propulsor. They also found significant alteration in vortex structures, leading to increased flow instability. Hur et al. [29] found that adding trailing edge serrations to axial-flow car cooling fans greatly lowered noise levels, with drops of up to 10 dB.

2.4. Controlled Diffusion Airfoil

Controlled Diffusion (CD) airfoils, designed specifically for subsonic and transonic flow conditions, play a key role in noise reduction studies. The broadband noise caused by stall and separation can vary depending on the angle of attack and Reynolds number [30]. The primary function of CD airfoils is to regulate flow separation, an essential aspect of noise reduction. Research indicates that flow reattachment happens ahead of the trailing edge at specific angles of attack, which results in less velocity disturbances and lower sound pressure levels (SPL) [31]. CD airfoils effectively decrease boundary layer detachment under transonic flow conditions by managing the diffusion over the airfoil section [32].

2.5. Morphing airfoil

A morphing airfoil's noise reduction mechanism entails modifying the airfoil's shape in real-time to maximize aerodynamic performance and manage sound production. According to recent research, by simulating high-lift configurations without appreciably increasing drag, morphing airfoils such as those created using shape optimization techniques can successfully reduce airframe noise during crucial stages like takeoff and landing [33]. Jawahar et al. [34] demonstrated how minor adjustments to the morphed flap's flap camber profile can have a big impact on the aerodynamic behavior. In comparison to the traditional hinged flap configuration, the morphed flap airfoil's boundary layer behavior demonstrated delayed separation. It was also discovered that there had been a significant change in the wake's turbulence levels, with the morphed flap having a larger magnitude.

2.6. Other Surface Modifications

Numerous studies have been conducted on surface treatments for airfoil noise reduction, and the results have shown a variety of useful tactics. Finlets are one method; when positioned optimally according to a dimensionless parameter, they can drastically reduce high-frequency noise by changing the vortex structure surrounding the airfoil [35]. Experimental comparisons of finlet rails and fences indicate that while both treatments provide moderate noise reductions, finlet fences are particularly effective at controlling mid- and high-frequency noise, whereas canopies are better for low frequencies [36]. Reducing the transversal spacing of finlet rails increases the maximum noise reduction, which was found to be 4 decibels at relatively low frequencies[37]. Figure 2(a) shows a close-up of a finlet treatment of a NACA 0012 airfoil trailing edge. Dimples can also be used which mostly entails changing the flow characteristics across the airfoil surface. Little vortices produced by dimples improve mixing and disturb the boundary layer, delaying separation and lowering pressure drag, which lowers noise emissions. It has been demonstrated that the inline arrangement of dimples placed strategically at one-third of the chord from the leading edge can significantly reduce noise by 6 to 8 dB, especially in the mid-to-high frequencies [38]. Dimple array orientation on an airfoil is shown in figure 2(b).

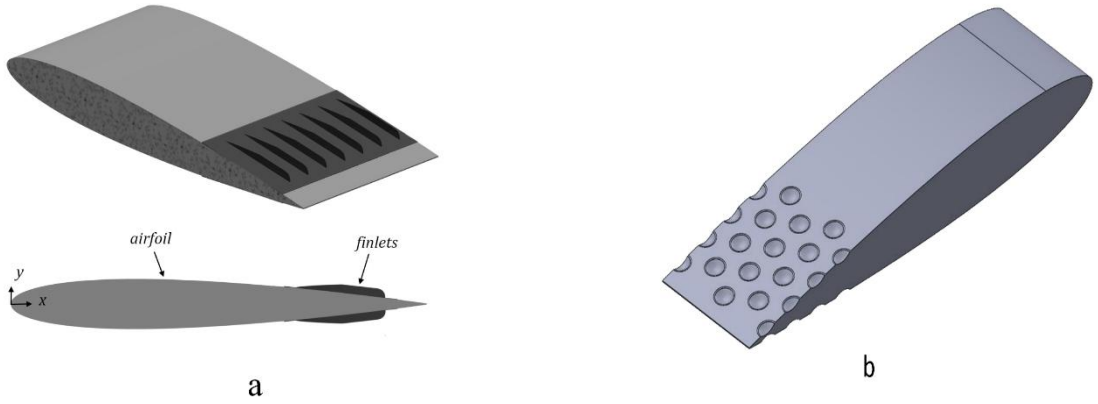


Fig. 2. (a) Finlet configuration, mounted on the NACA 0012 (left) [39] , (b) Dimple configuration (right) [40]

Table 1 outlines all these passive noise reduction methods, organized by their names, underlying mechanisms, frequency ranges they affect and the Reynolds number for each technique.

Table 1. Overview of Passive Noise Reduction Techniques

Method	Mechanism	Frequency Range	Reynolds Number	Noise Reduction (dB)	References
Leading Edge Modification	Turbulence Breakdown, Vortex Cancellation, Delay laminar-to-turbulent transition	Low to mid	Low to moderate	Upto 20	[27]
Trailing Edge Modification	Break down large vortices into smaller, weaker structures, Vortex Desynchronization, Reduced Flow Separation	Mid	High	7 to 10	[41]
Porous Materials	Flow Stabilization, Turbulence Damping, Vortex Reduction	Low to mid	Wide range	8 to 10	[42]
Serrations	Flow Attachment, Turbulence Disruption, Promotion of localized turbulence	Mid to high	Moderate to high	Upto 20	[43]
Controlled Diffusion Airfoil	Gradual Shape Change, Scatter and dissipate sound waves, Uniform flow distribution across the surface	Wide range	Moderate to high		[44]
Morphing Airfoil	Continuously adjusting the airfoil shape, prevent or delay flow separation	Low to mid	Wide range		[45]

Finlets	Prevent flow separation, minimizing vortex shedding and wake turbulence	Mid to High	Low to moderate	4	[36]
Dimpled Surface	Create small-scale turbulence, smooth out the transition from laminar to turbulent flow	Mid to high	High	6 to 8	[38]

3. Conclusion

This paper examines the latest developments in passive noise reduction techniques for airfoils, wings, and blades. It covers experimental, theoretical, and computational methods and talks about design techniques like surface treatments, morphing wings, porous materials, and leading/trailing edge serrations. The efficiency of each technique varies depending on the airfoil design, operating circumstances, and particular applications; a combination of techniques can frequently reduce noise over a wider frequency range. The study emphasizes the trade-offs between noise reduction and aerodynamic performance, pointing out that different approaches are needed for turbulent, transitional, and laminar flows. By adding to the expanding corpus of knowledge in the area, this review gives engineers and researchers a strong platform on which to build future developments in noise reduction technologies and a more environmentally friendly method of air travel. In order to support a quieter, more productive future for the aerospace industry, the insights offered here are intended to spur innovations that address the environmental impact of noise from high-lift devices.

4. References

[1] S. Moreau, P. Laffay, A. Idier, and N. Atalla, *Several noise control of the trailing-edge noise of a Controlled-Diffusion airfoil*. 2016.

[2] R. W. Paterson, P. G. Vogt, M. R. Fink, and C. L. Munch, "Vortex Noise of Isolated Airfoils," *Journal of Aircraft*, vol. 10, no. 5, pp. 296-302, 1973/05/01 1973, doi: 10.2514/3.60229.

[3] G. Desquesnes, M. Terracol, and P. Sagaut, "Numerical investigation of the tone noise mechanism over laminar airfoils," *Journal of Fluid Mechanics*, vol. 591, pp. 155-182, 11/01 2007, doi: 10.1017/S0022112007007896.

[4] S. Sinha, D. Cerizza, and W. Schuster, *Multiple Pure Tone Noise Predictions of a Propulsion Engine Fan with PowerFLOW*. 2023.

[5] M. Deuse and R. Sandberg, *Parametric study of multiple aerofoil self-noise sources using direct noise computation*. 2019.

[6] M. Roger, C. Schram, and L. De Santana, "Reduction of Airfoil Turbulence-Impingement Noise by Means of Leading-Edge Serrations and/or Porous Material," in *19th AIAA/CEAS Aeroacoustics Conference*, (Aeroacoustics Conferences: American Institute of Aeronautics and Astronautics, 2013.

[7] R. K. Amiet, "Acoustic radiation from an airfoil in a turbulent stream," *Journal of Sound and Vibration*, vol. 41, no. 4, pp. 407-420, 1975/08/22/ 1975, doi: https://doi.org/10.1016/S0022-460X(75)80105-2.

[8] R. Paterson and R. Amiet, "Acoustic radiation and surface pressure characteristics of an airfoil due to incident turbulence," in *3rd Aeroacoustics Conference*, (Aeroacoustics Conferences: American Institute of Aeronautics and Astronautics, 1976.

[9] J.-H. Kim *et al.*, "Aerodynamic and Aeroacoustic Optimization of Leading-Edge Undulation of a NACA 65(12)-10 Airfoil," *AIAA Journal*, vol. 60, no. 4, pp. 2342-2353, 2022/04/01 2021, doi: 10.2514/1.J060716.

[10] Y. Lu, Z. Li, X. Chang, Z. Chuang, and J. Xing, "An aerodynamic optimization design study on the bio-inspired airfoil with leading-edge tubercles," *Engineering Applications of Computational Fluid Mechanics*, vol. 15, no. 1, pp. 292-312, 2021/01/01 2021, doi: 10.1080/19942060.2020.1856723.

[11] S. S. Vemuri, X. Liu, B. Zang, and M. Azarpeyvand, "On the use of leading-edge serrations for noise control in a tandem airfoil configuration," *Physics of Fluids*, vol. 32, no. 7, p. 077102, 2020, doi: 10.1063/5.0012958.

[12] J. E. F. Williams and L. H. Hall, "Aerodynamic sound generation by turbulent flow in the vicinity of a scattering half plane," *Journal of Fluid Mechanics*, vol. 40, no. 4, pp. 657-670, 1970, doi: 10.1017/S0022112070000368.

[13] R. D. Sandberg and L. E. Jones, "Direct numerical simulations of airfoil self-noise," *Procedia Engineering*, vol. 6, pp. 274-282, 2010/01/01/ 2010, doi: https://doi.org/10.1016/j.proeng.2010.09.029.

[14] T. Nakano, N. Fujisawa, and S. Lee, "Measurement of tonal-noise characteristics and periodic flow structure around NACA0018 airfoil," *Experiments in Fluids*, vol. 40, pp. 482-490, 03/01 2006, doi: 10.1007/s00348-005-0089-2.

[15] C. Rao and H. Liu, "Aerodynamic robustness in owl-inspired leading-edge serrations: a computational wind-gust model," *Bioinspiration & Biomimetics*, vol. 13, no. 5, p. 056002, 2018/07/03 2018, doi: 10.1088/1748-3190/aacb43.

[16] A. Suryadi, S. Martens, and M. Herr, "Trailing Edge Noise Reduction Technologies for Applications in Wind Energy," in *23rd AIAA/CEAS Aeroacoustics Conference*, (AIAA AVIATION Forum: American Institute of Aeronautics and Astronautics, 2017.

[17] T. Geyer, E. Sarradj, J. Giesler, and M. Hobracht, *Experimental assessment of the noise generated at the leading edge of porous airfoils using microphone array techniques*. 2011.

[18] E. Sarradj and T. Geyer, *Noise Generation by Porous Airfoils*. 2007.

[19] T. Geyer, E. Sarradj, and C. Fritzsche, "Porous Airfoils: Noise Reduction and Boundary Layer Effects," *International Journal of Aeroacoustics*, vol. 9, no. 6, pp. 787-820, 2010/07/01 2010, doi: 10.1260/1475-472X.9.6.787.

[20] A. Tinetti, "On the use of surface porosity to reduce wake-stator interaction noise," 01/01 2001.
[21] M. Herr and J. Reichenberger, "In Search of Airworthy Trailing-Edge Noise Reduction Means," in *17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference)*, (Aeroacoustics Conferences: American Institute of Aeronautics and Astronautics, 2011.
[22] W. Zhu, J. Liu, Z. Sun, J. Cao, G. Guo, and W. Shen, "Numerical Study on Flow and Noise Characteristics of an NACA0018 Airfoil with a Porous Trailing Edge," *Sustainability*, vol. 15, no. 1, doi: 10.3390/su15010275.
[23] R. Zamponi *et al.*, "On the role of turbulence distortion on leading-edge noise reduction by means of porosity," *Journal of Sound and Vibration*, vol. 485, p. 115561, 2020/10/27/ 2020, doi: https://doi.org/10.1016/j.jsv.2020.115561.
[24] S. T. Go, M. Kingan, R. McKay, and R. Sharma, "Turbulent inflow noise produced by a shrouded propeller," *Journal of Sound and Vibration*, vol. 542, p. 117366, 10/01 2022, doi: 10.1016/j.jsv.2022.117366.
[25] J. Rottmayer *et al.*, "Trailing-Edge Noise Reduction using Porous Treatment and Surrogate-based Global Optimization," *arXiv [physics.flu-dyn]*, 2023 2023. [Online]. Available: http://arxiv.org/abs/2301.13047.
[26] T. P. Chong, A. Vathylakis, P. F. Joseph, and M. Gruber, "Self-Noise Produced by an Airfoil with Nonflat Plate Trailing-Edge Serrations," *AIAA Journal*, vol. 51, no. 11, pp. 2665-2677, 2013/11/01 2013, doi: 10.2514/1.J052344.
[27] C. K. Sumesh and T. J. S. Jothi, "Influence of Nonflat Plate Trailing Edge Serration on Airfoil Noise Reduction," *Journal of Aerospace Engineering*, vol. 37, no. 2, p. 04023122, 2024/03/01 2024, doi: 10.1061/JAEEEZ.ASENG-4995.
[28] C. Yang, C. Sun, C. Wang, H.-D. Yao, C. Guo, and Q. Yue, "Serration of the duct trailing edge to affect the hydrodynamics and noise generation for a pump-jet propulsor," *Physics of Fluids*, vol. 36, no. 1, p. 015140, 2024, doi: 10.1063/5.0180347.
[29] K. H. Hur, B. A. Haider, and C. H. Sohn, "Trailing edge serrations for noise control in axial-flow automotive cooling fans," *International Journal of Aeroacoustics*, vol. 22, no. 7-8, pp. 713-730, 2023/11/01 2023, doi: 10.1177/1475472X231206498.
[30] P. Jaiswal, J. Rendón, and S. Moreau, "Aeroacoustic investigation of airfoil at near-stall conditions," *Physics of Fluids*, vol. 35, no. 9, 2023.
[31] S. K. Kalyani, P. Jaiswal, J. Rendon, S. Moreau, and D. Ragni, "Flow-field and Noise Characterization of a Controlled-Diffusion Airfoil under stall," in *AIAA AVIATION 2023 Forum*, (AIAA AVIATION Forum: American Institute of Aeronautics and Astronautics, 2023.
[32] S. K. Kalyani, S. Moreau, and D. Ragni, "Flow-field and noise characterization of a controlled-diffusion airfoil," in *28th AIAA/CEAS Aeroacoustics 2022 Conference*, 2022, p. 2894.
[33] R. Valldosera Martinez, F. Afonso, and F. Lau, "Aerodynamic Shape Optimisation of a Camber Morphing Airfoil and Noise Estimation," *Aerospace*, vol. 9, no. 1, doi: 10.3390/aerospace9010043.
[34] H. Kamliya Jawahar, Q. Ai, and M. Azarpeyvand, "Experimental and numerical investigation of aerodynamic performance for airfoils with morphed trailing edges," *Renewable Energy*, vol. 127, pp. 355-367, 2018/11/01/ 2018, doi: https://doi.org/10.1016/j.renene.2018.04.066.
[35] B. Elhami, M. Dehghan Manshadi, and A. A. Dehghan, "Experimental investigation of typical surface treatment effect on velocity fluctuations in turbulent flow around an airfoil," *Chinese Journal of Aeronautics*, vol. 36, no. 10, pp. 112-123, 2023/10/01/ 2023, doi: https://doi.org/10.1016/j.cja.2023.06.020.
[36] S. Palani *et al.*, "Comparison of finlet rails and fences for trailing edge noise reduction in NACA0012 aerofoil," in *28th AIAA/CEAS Aeroacoustics 2022 Conference*, (Aeroacoustics Conferences: American Institute of Aeronautics and Astronautics, 2022.
[37] D. Fiscaletti, L. T. L. Pereira, and D. Ragni, "Finlet rails for the reduction of the trailing-edge noise," *Journal of Sound and Vibration*, vol. 568, p. 118072, 2024/01/06/ 2024, doi: https://doi.org/10.1016/j.jsv.2023.118072.
[38] S. Kumar, S. K. Singh, S. Jha, K. Baskaran, K. Srinivasan, and S. Narayanan, "On the reductions of airfoil broadband noise through circular dimples," *Applied Acoustics*, vol. 217, p. 109819, 2024/02/15/ 2024, doi: https://doi.org/10.1016/j.apacoust.2023.109819.
[39] F. Gstrein, N. Zang, and M. Azarpeyvand, "Application of Finlets for Trailing Edge Noise Reduction of a NACA 0012 Airfoil," in *AIAA AVIATION 2020 FORUM*, 2020, p. 2502.
[40] C. L. Perry, "Mitigation of Aeroacoustic Noise of a Fixed Wing Using Passive Flow Control," 2023.
[41] S. K. Singh, G. Shankar, A. Narayanmurthy, K. Baskaran, and S. Narayanan, "Effect of sawtooth trailing edge serrations on the reductions of airfoil broadband noise," *International Journal of Aeroacoustics*, vol. 23, no. 1-2, pp. 84-98, 2024/03/01 2024, doi: 10.1177/1475472X241226931.
[42] V. B. Ananthan, R. A. D. Akkermans, T. Hu, P. Q. Liu, and D. Burzynski, "Effects of localized application of porous material on trailing-edge noise of a circulation-controlled wing," *International Journal of Heat and Fluid Flow*, vol. 103, p. 109209, 08/22 2023, doi: 10.1016/j.ijheatfluidflow.2023.109209.
[43] S. K. Singh and S. Narayanan, "Control of airfoil broadband noise through non-uniform sinusoidal trailing-edge serrations," *Physics of Fluids*, vol. 35, no. 2, p. 025139, 2023, doi: 10.1063/5.0133556.
[44] Z. Ziyang, S. Moreau, and M. Sanjosé, "Direct Numerical Simulation of Installation Effects on Control Diffusion Airfoil Noise," in *AIAA AVIATION 2023 Forum*, (AIAA AVIATION Forum: American Institute of Aeronautics and Astronautics, 2023.
[45] Q. Ai, M. Azarpeyvand, X. Lachenal, and P. Weaver, "Airfoil noise reduction using morphing trailing edge," *21st International Congress on Sound and Vibration 2014, ICSV 2014*, vol. 2, pp. 1840-1847, 01/01 2014.